Confronting Neutron Star Cooling Theories with New Observations

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ABSTRACT

With the successful launch of *Chandra* and *XMM/Newton* X-ray space missions combined with the lower-energy band observations, we are now in the position where careful comparison of neutron star cooling theories with observations will make it possible to distinguish among various competing theories. For instance, the latest theoretical and observational developments appear to exclude both nucleon and kaon direct URCA cooling. In this way we can now have realistic hope for determining various important properties, such as the composition, degree of superfluidity, the equation of state and stellar radius. These developments should help us obtain better insight into the properties of dense matter.

Subject headings: Dense matter — stars: neutron — X-rays: stars

1. Introduction

The launch of the *Einstein* Observatory gave the first hope for detecting thermal radiation directly from the surface of neutron stars (NSs). However, the temperatures obtained by the *Einstein* were only the upper limits (e.g., Nomoto & Tsuruta 1986). *ROSAT* offered the first confirmed detections (not just upper limits) for such surface thermal radiation from at least three cooling neutron stars, PSR 0656+14, PSR 0630+18 (Geminga) and PSR 1055-52 (e.g., Becker 1995). Very recently, the prospect for measuring the surface temperature of isolated NSs, as well as obtaining better upper limits, has increased tremendously, thanks to the superior X-ray data from *Chandra* and *XMM/Newton*, as well as the data in lower energy bands from optical-UV telescopes such as *Hubble Space Telescope (HST)*. Consequently, the number of possible surface temperature detections has already increased to at least nine, by addition of RX J0822-4300 (Zavlin, Trümper, & Pavlov 1999), the Vela pulsar (Pavlov et al. 2001), RX J1856-3754 (Zavlin et al. 2002a), 1E 1027.4-5209 (Zavkin, Pavlov, & Trümper 1998), RX J0002+62 (Kaminker, Yakoblev, & Gnedin 2002), and RX J0720.4-3125 (Haberl, et al. 1997). Most recently Chandra offered an important upper limit to PSR J0205+6449 in 3C58 (Slane, Helfand and Murray 2002). It will be a matter of time when more detections, as well as better upper limits, will become available. These developments have proved to offer serious 'turning points' for the detectability of thermal radiation directly from NSs, because we can now seriously compare the observed temperatures with NS cooling theories (see., e.g., Tsuruta & Teter 2001a, 2001b, hereafter TT01a, TT01b). On the theoretical side, more detailed, careful investigations have already started. In this report we try to demonstrate that distinguishing among various competing NS cooling mechanisms already started to become possible, by careful comparison of improved theories with new observations.

2.   Neutron Star Cooling Models

The first cooling calculations (Tsuruta 1964) showed that NSs can be visible as X-ray sources for about a million years. After a supernova explosion a newly formed NS first cools via various neutrino emission mechanisms before the surface photon radiation takes over (e.g., Tsuruta 1979). Among the important factors which seriously affect the nature of NS cooling are: neutrino emission processes, superfluidity of the constituent particles, composition, and mass. In this paper, for convenience, the conventional, slower neutrino cooling mechanisms, such as the modified URCA, plasmon neutrino and bremsstrahlung processes which were adopted in many of the earlier and subsequent cooling calculations, will be called 'standard cooling'. On the other hand, the more exotic extremely fast cooling processes, such as the direct URCA processes involving nucleons, hyperons, pions, kaons, and quarks, will be called 'nonstandard' processes (see, e.g., Tsuruta 1998, hereafter T98).

The composition of the core is predominantly neutrons, with a small fraction of protons and electrons, if the density is moderate ($< \sim 10^{15}$ gm/cm^3). For higher densities hyperons, pions, kaons, quarks, etc., may dominate the central core. As the star cools after the explosion and the interior temperature falls below the superfluid critical temperature, T^{cr}, some hadronic components become superfluid. That causes exponential suppression of both specific heat (and hence the internal energy) and all neutrino processes involving these particles. The net effect is that the star cools more slowly (and hence the surface temperature and luminosity will be higher) during the neutrino cooling era. Very recently, the 'Cooper pair neutrino emission' (Flowers, Ruderman, & Sutherland 1976) was rediscovered to be also important under certain circumstances (see, e.g., Yakovlev, Levenfish, & Shibanov 1999). This process takes place right after the core temperature falls below T^{cr}, but it soon falls exponentially. The net effect is to enhance, for some superfluid models, the neutrino emission right after the superfluidity sets in.

We have calculated NS cooling adopting the most up-to-date microphysical input and the fully general relativistic, 'exact' evolutionary code (without making isothermal approximations) which was originally constructed by Nomoto & Tsuruta (1987) and has been continuously up-dated. All possible neutrino emission mechanisms both in the stellar core and crust, including the Cooper pair neutrino emission, are used. The results are summarized in Fig. 1, which shows the cooling curves of representative NSs with an equation of state (EOS) of medium stiffness, the FP Model constructed by Friedman & Pandharipande (1981). The solid curve refers to the standard cooling of a 1.2 M$_\odot$ star which consists predominantly of neutrons (with proton fraction of ~ 5 %). For this star the stellar core density, ρ_c, is below the critical density, ρ_{tr}, where the transition to the pion-condensed phase occurs. We adopt $\rho_{tr} = 2.5 \, \rho_0$ taken from Umeda et al. 1994 (hereafter U94), where $\rho_0 = 2.8$ x 10^{14} gm/cm^3 is

the nuclear density. For this star we adopt the T72 superfluid model (Takatsuka 1972) which is based on the most realistic treatment available for the neutron-dominated matter. We find that the superfluid effect is minor. This is because the superfluid gap (which is proportional to T^{cr}) depends on density, and the gap disappears at the maximum density, ρ_{max}, which is less than ρ_c, the central density of the star. On the other hand, the 1.4 $M_\odot$ star (dashed curve) cools by the pion cooling as the nonstandard case. This is because for this star the central density ρ_c exceeds ρ_{tr}, and hence the central core consists of pion condensates. As the superfluid model for the pion-condensed phase we adopt a medium superfluid gap model, called the E1-0.8 Model (see U94), which is constructed from the microphysical superfluid gap models calculated for the pion matter (Takatsuka & Tamagaki 1982, hereafter TT82). For this superfluid model both enhanced Cooper pair neutrino emission right below T^{cr} and subsequent suppression are significant. As the stellar mass increases from 1.2 $M_\odot$ to 1.4 $M_\odot$ the central density increases, and the corresponding stars lie between the solid and dashed curves in Fig. 1. Further details are found in TT01a, TT01b, Teter 2001, and Teter & Tsuruta 2002 (hereafter TT02).

3. Comparing Neutron Star Cooling Models with New Observations

In Fig. 1 cooling curves are compared with the latest confirmed observational data. We may note that the data in Fig. 1 suggest the existence of at least two classes of sources, hotter stars (e.g., (1) RX J0822-4300, (3) PSR 0656+14, (5) PSR RXJ 1856-3754 and (6) PSR 1055-52), and cooler stars (e.g., (c) PSR J0205+6449, (2) the Vela pulsar and (4) Geminga). The hotter sources are consistent with the solid curve, the standard cooling of a 1.2 $M_\odot$ star. The source (6) is somewhat above the solid curve, but that is easily explained when heating is included (see, e.g., Umeda, Tsuruta, & Nomoto 1994, hereafter UTN94) and when the age uncertainty, of a factor of ~ 2, is taken into account. On the other hand, the cooler stars are consistent with the dashed curve, the pion cooling of a 1.4 $M_\odot$ star with significant superfluid suppression. (The age uncertainty should not affect this conclusion for younger sources because the slope of the curves in these younger years is small.) The conclusion is that the observed data are all most naturally explained as the effects of stellar mass and superfluidity of the constituent core particles.

At least for binary pulsars, recent observations offer stringent constraints on the mass of a NS, to be very close to 1.4 $M_\odot$ (e.g., Brown, Weingartner, & Wijers 1996). If this evidence extends to isolated NSs also, then the EOS should be such that the mass of the star whose central density is very close to the transition density (where the nonstandard process sets in) should be very close to 1.4 $M_\odot$. With the EOS of our current choice, medium FP Model,

that transition takes place between 1.2 $M_\odot$ and 1.4 $M_\odot$. Then if the deviation from the 'magic number' 1.4 $M_\odot$ should be very small the correct EOS may have to be somewhat stiffer than medium. This is because a stiffer EOS corresponds to somewhat larger mass, for given transition density, and hence the corresponding mass for the solid and dashed curves will become, e.g., 1.35 $M_\odot$ and 1.45 $M_\odot$, respectively, instead of 1.2 $M_\odot$ and 1.4 $M_\odot$. In this way comparison of cooling curves with observation has a potential for determining the EOS and hence radius, if the mass is fixed. Note that comparison of this kind already eliminates very soft and very stiff EOS. The reason is that a very soft EOS will be so compact and the density so high that the phase transition will take place for stars of too small mass, e.g., $\sim$ 0.3 $M_\odot$. On the other hand, the central density of stars with a very stiff EOS will be below the transition density, meaning that the dashed curve can never exist.

The qualitative behavior of all nonstandard scenarios is similar if their transition density is the same (see, e.g., UTN94, T98). However, here we try to demonstrate that it is still possible to offer comprehensive assessment of at least which options are more likely while which are less likely. First of all, we note that all of the nonstandard mechanisms are too fast to be consistent with any observed detection data, even with heating (see, e.g., UTN94, T98). That means *significant suppression of neutrino emissivity due to superfluidity is required*. However, recently Takatsuka & Tamagaki (1997)(hereafter TT97) showed, through careful microphysical calculations, that for neutron matter with high proton concentration which permits the nucleon direct URCA, the superfluid critical temperature T^{cr} should be too low, $\sim$ several x 10^7 K, both for neutrons and protons. On the other hand, the observed NSs, which are to be compared with cooling curves, are all hotter (the core temperature being typically $\sim 10^8$ K to several times 10^8 K). That means *the core particles are not yet in the superfluid state* in these NSs. The implication is that *these sources would be too cold if nucleon direct URCA were in operation.* The same argument applies to the kaon cooling also (Takatsuka & Tamagaki 1995, hereafter TT95).

Recently, Kaminker, Yakovlev, & Gnedin 2002 (hereafter KYG02) carried out cooling calculations similar to ours by adopting the nucleon direct URCA as the nonstandard option. However, as just pointed out, *the observed NSs adopted for their comparison would be yet to be in the superfluid state*, and hence these stars would be too cold if the nucleon direct URCA cooling were in operation. The calculations by KYG02 led to two important conclusions concerning the core superfluids: (i) proton superfluid critical temperature, T_p^{cr}, should be relatively high, ~ 7 x 10^9 K, if the nucleon direct URCA is to be in operation in the observed cooler NSs; while (ii) the neutron superfluid critical temperature, T_n^{cr}, should be less than 10^8 K, for the same superfluid model to be consistent with the data of hotter NSs. The conclusion (ii) agrees with realistic microphysical calculations of the neutron matter with high proton concentration which allows the nucleon direct URCA (TT97), but the conclusion (i)

contradicts with these microphysical results. We may note that KYG02 did not actually carry out microphysical calculations, but only assumed that the $^1S_0$ superfluid gap of neutrons and protons are similar and also that the proton effective mass is 0.7 m_p (where m_p is bare proton mass). Both assumptions, however, are not justified (see, e.g., TT95, TT97). Also, their empirically constructed T_p^{cr} is based on the microphysical gap calculations carried out for 'conventional' neutron matter with only very small proton fraction. However, in order for the nucleon direct URCA to work, the proton fraction must be high, ~ 15 % or more (Lattimer et al. 1991). Then, there will arise two important microphysical factors to *suppress* the realization of proton superfluidity. One is that the proton effective mass decreases with increasing ρ and should be less than $\sim 0.6 m_p$, even if such high proton concentration phase could be realized at rather low densities ($\rho \gtrsim (2-3)\rho_0$). The other is that the repulsive core effect in the $^1S_0$ pairing interaction, which grows with increasing proton fraction, becomes more significant. The growth of this effect means the reduction of attraction in the pairing interaction, and hence a smaller energy gap. These two factors indeed *reduce* T_p^{cr} to *below* 10^8 K for the density regime where nucleon direct URCA can take place. We emphasize that this qualitative tendency is *not* model-dependent (TT97). Note that both effective mass and the attractive effect in the pairing interaction depend sensitively on composition, as well as density, – these values for neutron matter with low proton fraction ('conventional' neutron matter) and high proton fraction (the matter which permits nucleon direct URCA) should be quite different (TT97).

Furthermore, recent theoretical developments point to some additional theoretical problems concerning the realization of the nucleon direct URCA itself. For instance, Engvik, et al. (1997) (hereafter E97) and Akmal, Pandharipande and Ravenhall (1998) (hereafter APR98) studied the symmetry energy in nuclear matter adopting various new potentials (sometimes called the 'modern potentials'), and have shown that the direct URCA cannot occur, at least below ~ 5 times the nuclear density, for all potentials. (If the transition is to occur at such high density, the EOS will have to be too soft, to be consistent with observation.) See also the very recent paper by Heiselberg & Pandharipande (2000) (hereafter HP00), which reviews the current status of microphysical calculations of nuclear matter with the modern potentials, and points out the consistency among various results obtained by different methods, especially for neutron matter. For instance, the results by E97 which is based on the Brueckner theory, and those by APR98 which is based on a variational calculation, are consistent.

The difficulties with the nucleon and kaon direct URCA options just pointed out leave as still possible nonstandard options the direct URCA involving pions, hyperons or quarks. Hyperons may appear at densities as low as $\sim (2-3)\rho_0$ (e.g., Prakash, et al. 1992). Recently, Takatsuka and Tamagaki (1999, 2001) and Takatsuka, et al. (2001) investigated hyperon su-

perfluidity by using several hyperon-hyperon pairing interactions, and conclude that hyperon cooling may be consistent with the observed detection data of cooler stars. Therefore we are currently exploring the hyperon cooling option (Tsuruta et al. 2002). The problem for quarks, however, is that theoretically there are still too many unknown factors to offer the level of exploration possible for the other options (see Tsuruta, et al. 2002).

As to the pion direct URCA option, it has been already shown, through detailed microphysical calculations, that T^{cr} could be several times 10^9 K, higher than the nucleon and kaon direct URCA cases, and so quasi-baryons in the pion-condensed phase should safely be in the superfluid state for the observed cooler NSs. This is mainly because the effective mass of quasi-baryons is higher in the pion-condensed phase, $\sim (0.8 - 0.9)m_N$, where m_N is the bare nucleon mass (TT82). Note that the superfluid gap model adopted for the dashed curve in Fig. 1 is based on realistic microphysical theories (TT82, U94, TT02). The conclusion is that *the pion cooling is consistent with both theory and observation.*

It may be noted that very recent theoretical developments indeed assures the presence of pion condensates in the relatively low density regime which is consistent with our pion cooling models. For instance, Akmal & Pandharipande (1997) carried out a variational calculation of nuclear matter by using a modern potential, and found that both symmetric nuclear energy matter and pure neutron matter undergo transitions to pion condensed phase at relatively low densities. Furthermore, adopting the most recent experimental data on the giant Gamow-Teller resonance, Suzuki, Sakai & Tatsumi (1999) reexamined the threshold conditions for pion condensation, and reached similar conclusion. See also the review by HP00 which supports this conclusion.

4. Summary and Concluding Remarks

We have shown that the most up-to-date observed temperature data are consistent with the current NS thermal evolution theories if slightly less massive stars cool by standard cooling while slightly more massive stars cool with nonstandard cooling. Among various nonstandard cooling scenarios, both nucleon and kaon direct URCA cooling appears to be excluded due to the high proton concentration required, which lowers the critical superfluid temperature. Then, the cooler stars must possess a central core consisting of pions, hyperons or quarks. The pion cooling is already shown to be consistent with both observation and theory. Comparison of cooling curves with observations already eliminates both very stiff and very soft EOS if the stellar mass is close to 1.4 $M_\odot$. That means the radius should be around 10 – 12 km, but not ~ 7 km (soft EOS) nor ~ 16 km (stiff EOS).

The capability of constraining the composition of NS interior matter purely through observation alone will be limited, and hence it will be very important to *exhaust all theoretical resources*. Theoretical uncertainties can be large, especially in the supranuclear density regime, but here we emphasize that we should still be able to set *acceptable ranges*, at least to separate models more serious from those merely possible. More and better data expected soon from *Chandra*, *XMM/Newton*, *HST*, and the 3rd generation missions already scheduled for the near future, when combined with improved theories, should give still better insight to some fundamental problems in dense matter physics.

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Figure Caption

Fig.1.– Cooling curves for stars with the medium FP EOS. The surface photon luminosity which corresponds to surface temperature (both to be observed at infinity) is shown as a function of age. The solid curve shows standard cooling of a 1.2 $M_\odot$ NS with the T72 superfluid model, while the dashed curve is the nonstandard pion cooling of a 1.4 $M_\odot$ star with the E1-0.8 superfluid model. (See the text for the definitions and further details.) The vertical bars refer to confirmed surface temperature detection with error bars, for (1) RX J0822-4300, (2) the Vela pulsar, (3) PSR 0656+14, (4) Geminga, (5) RX J1856-3754, and (6) PSR 1055-52. The downward arrows refer to the temperature upper limits for (a) Cas A point source, (b) Crab pulsar, (c) PSR J0205+6449, (d) PSR 1509-58, (e) PSR 1706-44, (f) PSR 1823-13, (g) PSR 2334+61, (h) PSR 1951+32, (i) PSR 0355+54, and (j) PSR 1929+10. The references are: Zavlin et al.1999 for (1), Pavlov et al. 2001 for (2), Zavlin et al. 2002b for (3), Halpern & Wang 1997 for (4), Zavlin et al. 2002a and Walter and Lattimer 2002 for (5), Pavlov et al. 2002 for (6), Pavlov et al. 2000 for (a), and Slane et al. 2002 for (c). The rest are taken from Becker 1995. In spite of possible positive detections, sources 1E 1027.4-5209, RX J0002+62, and RX J0720.4-3125 are not shown in Fig. 1 because currently there are still some uncertainties including the age estimate.
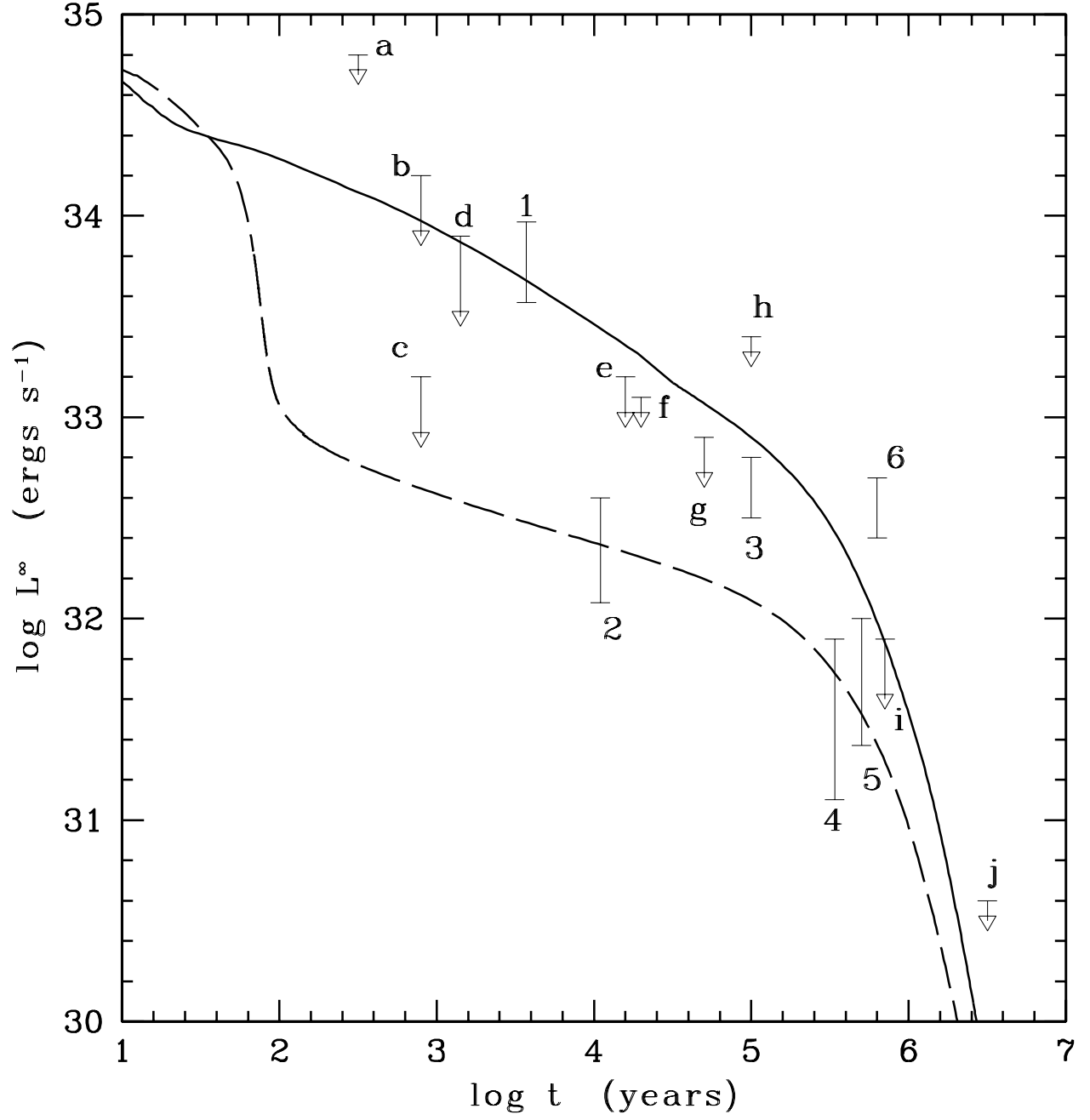
Fig. 1.— see previous page